Fold-thrust structures – where have all the buckles gone?

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ABSTRACT: The margins to evolving orogenic belts experience near layer-parallel contraction that can evolve into fold and thrust belts. Developing cross-section scale understanding of these systems necessitates structural interpretation. However, over the past several decades a false distinction has arisen between some forms of so-called fault-related folding and buckle folding. We investigate the origins of this confusion and seek to develop unified approaches for interpreting fold and thrust belts that incorporate deformation arising both from the amplification of buckling instabilities and from localized shear failures (thrust faults). Discussions are illustrated using short case studies from the Bolivian Subandean chain (Incahuasi anticline), the Canadian Cordillera (Livingstone anticlinorium) and Subalpine chains of France and Switzerland. Only fault-bend folding is purely fault-related and other forms, such as fault-propagation and detachment folds all involve components of buckling. Better integration of understanding of buckling processes, the geometries and structural evolutions that they generate, may help to understand how deformation is distributed within fold and thrust belts. It may also reduce the current biases engendered by adopting a narrow range of idealized geometries when constructing cross-sections and evaluating structural evolution in these systems.

Introduction

A key goal for many studies of continental tectonics is to relate folds, faults and distributed strain to create reliable geometric interpretations of three dimensional structure. For many decades much of this work has been allied to the exploration of earth resources, especially oil and gas. Since the early 1980s, descriptions of fold-thrust complexes (e.g. Suppe 1983; Jamison 1987), with application to subsurface interpretation (e.g. Shaw et al. 2005), have led to mechanical approaches (e.g. Smart et al. 2012; Hughes & Shaw 2015) that rely on a very narrow range of deformation styles. Elsewhere we argue that this emphasis has created significant bias in the ways larger-scale structural interpretations are built and their uncertainties assessed (Butler et al. 2018). Here we discuss how the basic concepts of buckle folding, the principles of which are laid out by Ramsay (1967), may help to reduce an over-reliance on a biased set of fold-thrust models. Buckling is the process by which layers fold when subjected to contraction along their lengths. Research on this folding mechanism has continued in parallel with that on fold-thrust belts. Our aim here is to draw these lines of research together, pooling knowledge and, consequently reunite interpreters of fold-thrust systems with key components in the structural toolkit that is *Folding and Fracturing of Rocks* (Ramsay 1967).

First, we briefly outline an evolution of ideas on fold-thrust interpretations – as this history underpins the majority of existing approaches to folding and faulting in compressional regimes. We then examine the approaches through which current understanding of buckle folds has developed in parallel to these fold-thrust models. We apply these concepts to challenge the notion that detachment folds and buckle folds are somehow distinct. We then examine some case studies to show how buckling concepts may better inform structural understanding. To unify these different approaches to better understand folding and its relationship to faulting, we examine structures in terms of their evolution of deformation localization. This informs a reassessment both of detachment folding and fault propagation folding that sit within the family of current fold-thrust models. Rather than interpret deformation in terms of idealized geometries, and considering folding to be a consequence of faulting, we argue that it is better to view structures as lying in a continuum of possible geometries and localization behaviors (Butler 1992).

Much existing work examines structural evolution through cross-sections, seeking explanations for fold-thrust interactions in these single illustrative planes. We challenge this notion, developing concepts of lateral fold growth inherent in buckling models, to argue that even if illustrated by cross-sections, structural understanding is better served through considering how deformation evolves in three dimensions.

Fold-thrust structures – an introduction (the tyranny of concentric folding)

The sedimentary rocks on the flanks of mountain belts, ancient and modern, commonly show the effects of horizontal contraction, manifest as thrust faults and folds. These structures have been studied for centuries – and current perspectives on the developments of interpretations and concepts are provided by many authors (e.g. Frizon de Lamotte and Buil 2002; Groshong et al. 2012; Brandes and Tanner 2014; Butler et al. 2018). These generally recognize the importance of work, especially in the foothills of the Canadian Cordillera, reported by Dahlstrom (1969, 1970; but see also Fox 1959; and Bally et al. 1966). This was largely driven by the exploitation of oil and gas hosted in complex fold-thrust structures.

<u>Origins</u>

Subsurface interpretation in frontier fold-thrust belts, be that in the 1960s in the Canadian cordillera of Alberta, or in the 2000s-present in the Papuan fold belt (e.g. Parish 2015), is an exercise in uncertainty management. It is generally driven by outcrop geology and existing wells, which provide directly measured dip and horizon data, but of great complexity. This is allied with regional 2D seismic profiles that, for the Canadian cordillera in the 1960s, were of poor quality and thus only resolved simple structural components. In effect the seismic data crudely imaged the top of the underlying basement to be gently dipping, apparently planar and therefore the complex structures in the sedimentary cover were detached from it. The deformation was “thin-skinned”. The challenge, as met by Dahlstrom (1969, 1970), was to elaborate a workflow for constructing cross-sections through the volume of thin-skinned deformation that forecast subsurface structure before any further drilling. The first step lay in simplification. Dahlstrom defined a narrow range of components that should be used in section construction, his so-called “foothills family” of structures. These are: concentric folding; décollement; thrusts (usually low angle and often folded); tear faults; and late normal faults. The second part lies in testing cross-section-scale interpretations for internal consistency. This was achieved by structural restoration and thus the notion of balanced cross-sections was formally defined (Dahlstrom 1969). In such sections, the sinuous bed-length for each stratigraphic horizon measured in the interpreted structure have an equal length in the pre-deformation state. Thus, restorable cross-sections are demonstrations of strain compatibility – all horizons display the same longitudinal strain in the section plane. When first developed by Dahlstrom (1969), this method required no distortional strain within the beds ("bed-length balancing") and the strata must have been parallel-bedded before deformation (so-called "layer-cake stratigraphy"). These restrictions require structures to approximate to concentric folds. Subsequent development of section balancing concepts have lifted these restrictions. For example, Woodward et al. (1986) and Geiser (1988) discuss the incorporation of explicit strain measurements into cross-section restoration and Butler (1992) developed the method of formation area balancing, trading off strain-related thickness changes against pre-existing stratigraphic thickness variations. Thus, interpretations could be tested using structural restoration even where pre-existing stratigraphy was laterally variable and distortional strain is heterogenous through multilayers.

<u>Upscaling and downscaling</u>

The success of adopting the foothills family of structures, and the rigor of creating balanced cross-sections, in forecasting subsurface structure in Alberta was recognized and promoted by Elliott (Elliott and Johnson 1980; Boyer and Elliott 1982). In essence these approaches are about up-scaling local geology and so in turn led to widespread reinvestigation of regional structure of thrust systems and their relationship to orogenic belts around the world. Some of these studies (e.g. Butler 1986) explicitly simplify outcrop structure by adopting the foothills family to minimize the implicit values of orogenic contraction experienced by thrust belts, for example, to compare with volumes of continental crust beneath mountain belts. As such they make no claims of precision for the structure of the thrust belts themselves.

Decisions on how to simplify structures on cross-sections vary depending on the scientific objective. Arbitrary choices such as solutions with minimum horizontal shortening may be appropriate for upscaling to deduce crustal-scale tectonic processes (e.g. Butler 2013), but not if the aim is to understand the relationships between individual folds and thrusts. Downscaling to forecast the location of specific stratigraphic units in the subsurface, or to relate strain and fracture patterns to fold development require different approaches. Consequently, Dahlstrom's (1969; 1970) "foothills family" of structures was developed into quantitative geometric approaches for describing relationships between folds and thrusts (e.g. Suppe 1983; Jamison 1987; Mitra 1990). In this way, folding is considered kinematically and thus to be a consequence of the geometry, displacement and propagation of thrust faults. On this basis, Jamison (1987) formalized the types of fault-related folds that can develop (Fig. 1).

If bed thickness is conserved during deformation, a requirement for concentric folding, only a very narrow range of viable geometries also yield balanced cross-sections (e.g. Suppe 1983). This restriction leads directly to explicit geometric "rules" and these underpin algorithms in structural modeling software (Groshong et al., 2012). In his trishear model, Erslev (1991) relaxed the requirement for bed-thickness conservation - but only in the forelimb of fold-thrust structures. Shaw et al. (2005) review all these models, with application to seismic interpretation while Groshong et al. (2012) and Brandes and Tanner (2014) review their history.

Just as Dahlstrom's (1969, 1970) approaches were driven by a need to reduce interpretation uncertainty when forecasting the subsurface structure in the pursuit of oil and gas, recent developments have also had economic drivers. Many applications of fold-thrust models aim to forecast small-scale faults and fractures down-scaling from larger fold-thrust structures. Consequently there have been various mechanical developments from the kinematic models described above (e.g. Kampfer and Leroy 2012; Smart et al. 2012; Hughes et al. 2014; Hughes and Shaw 2015). Note however that these mechanical models generally assume a specific kinematic evolution and are applied to a single fold-thrust structure, or a layer within it. The implications of adopting these approaches are discussed later.

Buckle folding – an introductory review

Similar to fold-thrust structures, buckle folding has a history of research stretching back well over half a century. However, buckling research has been less concerned with forecasting poorly known subsurface structure. There are several excellent discussions on buckle folding, building on the pioneering studies of Ramberg (1966) and Biot (1961). Ramsay (1967) provided an early overview of these works and this spawned extensive research, especially using analogue materials with measurable viscosities (chiefly plasticine and gelatin). Many of these results are reviewed by Price and Cosgrove (1990) who provide a comprehensive account of buckling processes. Subsequently, with enhanced computing capability, numerical methods have been increasingly adopted to understand these processes (e.g. Abbassi and Mancktelow 1992; Mancktelow and Abbassi 1992; Casey and Butler 2004; Schmalholz 2008; Reber et al. 2010). Very little of this content is considered in thrust belt literature and so here we provide a (re) introduction, much of which may be familiar to those currently engaged in buckle research. A compilation of some buckling concepts is outlined in Fig. 2.

For a given imposed layer-parallel contraction, the geometry of folds in a single competent layer embedded in a lower viscosity matrix will depend on the thickness of the layer and its viscosity in contrast to the matrix (Fig. 2a). Higher viscosity contrasts favor concentric folding. Longer wavelengths are developed in thicker layers. Ramberg (1966) and Biot (1961) independently established that there is a cube-root relationship between layer thickness and wavelength so, as Price and Cosgrove (1990), note, in multilayers of constant viscosity contrasts (e.g. bedded turbidite sandstones and shales, or thick limestones with interbedded shale formations), it is the thicker beds that will dictate the wavelength of the resultant fold belt. They term such beds "*control units*".

Single-layer buckles are encased in a deformed matrix. Based on reports of analogue experiments, Ramsay (1967) illustrates how this deformation varies away from a competent buckled layer through a zone of contact strain (Fig. 2b). These patterns have been reproduced numerically by Reber et al. (2010; Fig 2c).

As the buckled layer is created by layer-parallel shortening, the long-axes of strain ellipses in the zone of homogeneous strain away from the buckled layer (represented by the long-dimension of the originally square elements in the rectilinear grids of Figs 2 b,c) is orthogonal to the original orientation of the layer. In nature this attribute will be tracked by axial-planar cleavage associated with the folds.

Based on approaches of Latham (1985; reviewed by Price and Cosgrove 1990), Casey and Butler (2004) argue for a complex evolving relationship between strength and imposed shortening (Fig. 2d). Planar competent layers have a bending resistance that must be overcome if folds are to amplify significantly. This is particularly important for anisotropic materials – such as well-bedded units. Once bending resistance is overcome, folding is efficiently achieved through near-rigid limb rotation. Stress increases initially until the bending resistance of a layer is overcome, at which point there can be a dramatic stress drop throughout this deforming layer. Deformation can progress readily by limb rotation until limited by interlimb angle. Folds will then tend to lock up.

Faulting and folding

Rheological multilayers can deform by buckling and thrusting. Although these are distinct forms of mechanical instability, extensive analogue modelling (reported by Price and Cosgrove 1990) demonstrates that these can co-exist during the same deformation (Fig. 2e). Continued deformation may result in faults propagating into previously unfaulted, folded layers, or becoming shut-down and folded if adjacent buckles amplify appropriately.

Using well-exposed coastal outcrops along the flanks of Oslo Fiord, Morley (1994) describes arrays of thrusts that apparently relate to over-tightening of fold hinges, rather than having formed as linked fault networks. Morley's interpretations are a rare published example that folds can contain minor faults, despite their description by Ramsay (1967, p. 421). Price and Cosgrove (1990) class these as accommodation structures (Fig. 3a, b). They note that such structures tend to concentrate in the hinges of folds and are preferentially developed in competent layers adjacent to thicker beds (control units) that are dictating the overall fold shape (Fig. 3c). The types of faults are characteristically rootless and pass onto segments of bedding planes. Examples include "out-of-syncline" thrusts (Dahlstrom 1970).

There have been a few attempts to identify accommodation faults in thrust belts. Mitra (2003) reports many examples, including within the Ventura Avenue Anticline of Southern California (Fig. 3d). Well data reveal multiple thrusts that accommodate thickening of the Pico Formation (Pliocene), yet these thrusts appear not to cut deeper horizons or continue to outcrop. Similar behavior is interpreted by Boyer (1986) in his consideration of the Anschutz Ranch East Field in the Wyoming Overthrust Belt (Fig. 3e). Here too, well penetrations identify complex faulting along the hinge of a tight fold within the Preuss/Stump Formation (Jurassic). The fold appears to be controlled by a competent layer at depth defined by the Nugget Sandstone and Twin Creek Limestone. The accommodation fault passes into incompetent evaporites.

Fold trains

In contrast to the fold-thrust structures presented earlier (Fig. 1), buckle folds are generally not considered in isolation, but rather as arrays. For example, analogue experiments by Dubey and Cobbold (1977) demonstrated that folds form in trains and that they propagate laterally as they amplify (Fig. 4a, b). The initial fold systems initiated in clusters on inherited flaws in the plasticine multilayer. However, these clusters grew out laterally. Folds from different clusters can collide. Where folds are in phase they can combine to create long, fully-connected hinge lines. Fold mergers like this, although long recognized, are similar to behaviours more recently deduced for segment-linkage in the formation of large normal faults (e.g. Cartwright et al. 1995). However, other folds may remain segmented generating abrupt plunge terminations (see also Casey and Butler 2004; Fernandez and Kaus 2014). Progressive deformation establishes a dominant wavelength of the fold train, overprinting the initial distribution of perturbations that may have seeded the initial folds.

Multilayer fold trains

Dixon and Lui (1992) performed folding experiments in analogue materials that demonstrate the lateral growth of buckle systems. The model illustrated here (Fig. 5a, b) shows a series of three thick competent layers (X, Y, Z) separated by low-viscosity material within which is encased a highly competent marker (contorted blue line in Fig 5a, b). Comparison of the two deformation states (Fig. 5a evolves into Fig. 5b) shows how the folds grow. Although the multilayer contains low viscosity levels, the folds in the competent units are broadly in harmony. The experiment shows, that although folds may grow across a model (Fig. 5a, b), once formed, they can amplify together. The overall fold train geometry is controlled by the thicker units, confirming the reports by Price and Cosgrove (1990). The models also illustrate how the structure of fold hinges in these control units (X, Y, Z) can influence deformation. Consider fold III in Fig. 5b. The upper layer (X) has ruptured by crestal faulting allowing the fold limbs to rotate, greatly decreasing the interlimb angle. This in turn influences the structure of the underlying thin layer. In nature, these behaviours would likely be facilitated by erosion of the antiform crest. It is not just the upper layer (X) that develops tight folds. The middle control unit (layer Y) has tight interlimb angles (e.g. folds IV and VI in Fig. 5b). These layers are locally faulted in their forelimbs.

Multilayer folding has also been investigated in 3D finite element models. The examples shown here (von Tscharner et al. 2016; Fig. 5c, d) illustrate the stratigraphic control on disharmonic deformation. Here bucking is developed in competent units against a step that mimics a basement fault. If the incompetent matrix (green in Fig. 5c, d) is thick above the basement then the two competent layers can fold harmonically. A thinner low-viscosity layer immediately above the basement promotes disharmonic deformation.

Detachment folding and buckle folding: a false distinction?

Groshong (2015) makes an explicit distinction between detachment folds and buckles, although both systems can develop above fixed décollement levels. For his definition of detachment folding, the antiforms rise away from the décollement, creating an "excess area" beneath a specific horizon that is equal to the amount of horizontal shortening multiplied by the height of the horizon above the detachment away from the fold (Fig. 6a). In contrast, he conceptualizes buckling with uplift of the anticline crest but with net subsidence beneath synclines (Fig. 6b). Likewise, Mitra (2003 see also Ghanadian et al., 2017) illustrates buckling of above décollement surfaces where ductile material is evacuated beneath synclines and flows into anticline hinges.

Note that the basic conceptualization of buckle folding (Figs 2b, c), developed both from analogue experiments and from numerical modeling, does not show evacuation beneath synclines. Consider the state of finite strain around single layer buckle folds. Some classical buckling models (e.g. Fig. 2b) depict outer-arc stretching tangential to fold hinges (e.g. Ramsay 1967; Price and Cosgrove 1990). However, these strain states are restricted to within, or are immediately adjacent to, competent layers. More generally, single layer buckles are shown to pass out into homogeneous strain that accommodates shortening (Figs 2b, c). As noted earlier – this predicts axial planar cleavage – in antiforms and synforms alike. If Groshong's (2015) assertions are correct, in regions of horizontal sub-contraction, cleavage would be axial planar in the antiforms (near upright) but sub-perpendicular to synform axial surfaces (near horizontal). These relationships are certainly not generally observed in regions of distributed folding, such as slate belts (e.g. Coward and Siddans 1979; Woodward et al. 1986).

Perhaps the confusion of buckling has arisen because of the way in which results of analogue experiments have been reported. This is illustrated in Fig 6c, using an experiment of progressive deformation described by Cobbold (1975, fig. 5) on buckling in heterogeneous paraffin wax. His images are redrafted here in colour with added labelling for reference. The original model was set up with a single competent layer (X on Fig. 6c), embedded within a matrix of lower viscosity upon which were printed reference lines, parallel to the competent layer and the lower edge of the deformation apparatus. One of these reference lines is labelled here (Y on Fig. 6c). The aim of Cobbold's study was to chart the amplification of folds and so his illustrations focus on the buckled competent layer itself (X on Fig. 6c), centered through the middle of the growing fold. Consider the low strain state with the left-hand high strain image (Fig. 6c) - the frame of reference of the initial location of the competent layer relative to the deformation apparatus is lost. Cobbold's images are cropped, as evidenced by the trimming of the printed pre-deformation reference lines between successive deformation states. If the images are rehung relative to the pre-deformation reference lines (e.g. Y on Fig. 6c), the control layer X is shown to have moved upwards (right hand high strain state in Fig. 6c). There is no subsidence of the synforms and the surrounding deformation is broadly as described by Ramsay (1967, Fig. 2a) and others since.

The key for analysing fold development is to relate the deformation of a layer to its “Regional”. The term “*Regional*”, as applied to a deformed horizon and formalized by Williams et al. (1989), is short-hand for “regional orientation and elevation” of that horizon at a scale significantly greater than of a particular deformation structure. It is easiest to apply in sedimentary basins, where the “regional” describes the very long-wavelength of a particular horizon. The behavior of the horizon relative to its “regional” is diagnostic of tectonic regimes. Extensional faulting drops rocks below their regional. Contractional faulting brings rocks above their “regional”. These are net behaviours and are especially useful for analyzing reactivation of faults (see Williams et al. 1989). As implied by the strain state shown by Ramsay (1967, p. 417), the folded competent layer is raised above its “regional” throughout. It is differential but still upward movement of the buckled layer that creates antiforms and synforms. Nowhere in the model is there subsidence.

The “regional” concept can be applied to the analogue model experiments in Fig. 6c. Here it is the mis-identification of the “regional” for the base of the competent layer (X) in the left-hand illustration that leads to the false deduction of synform subsidence. When the higher strain state is rehung using the deeper marker horizon (Y, the right hand illustration), the “regional” for the base of the control layer moves down. This is a minimum illustration for the location of the “regional”, because if the levels in the model beneath the marker horizon are involved (as they were, when considering the low-strain state), the original location of the control layer (X) would move further down still. This example is consistent with the illustrations of Ramsay (1967; Fig. 2a).

In areas of no imposed longitudinal strain, rocks can still move relative to their “regionals” as a consequence of redistribution of material at depth, for example due to salt flow. In this case, subsidence beneath salt-withdrawal basins (a pre-kinematic stratum goes below its "regional") is compensated for by uplift of a salt pillow (the same pre-kinematic stratum goes above its "regional"). It appears to be characteristic of systems that have a thick layer of exceptionally low-viscosity material at depth. Subsidence of synclines is driven by deposition of syn-kinematic strata – so-called "down-building".

Simpson (2009) provides results from numerical modelling that explores the geometry of fold and thrust structures that form above low-viscosity layers in decollement zones (Fig. 6 d, e). These models use exceptionally low viscosities, perhaps appropriate to salt or over-pressured mud. Deformation of the competent beam above this material generates arrays of buckle folds together with localized shears, equivalent to thrusts. Where the low-viscosity zone is thin, the synclines in overlying competent units remain above their "regional" (Fig. 6e). In contrast, where the low-viscosity zone is thick, the synclines subside below their "regional" (Fig. 6d) While these behaviours may be appropriate to some submarine thrust systems at the toes of gravitationally spreading sedimentary prisms, it is not obvious that these models are applicable to foreland fold and thrust belts. Exceptions may include those fold belts that include thick evaporite sequences at depth, such as the Provencal sector of the French Alps (Graham et al. 2012) and the Fars sector of the Zagros (e.g. Mouthereau et al. 2007). Note that syncline subsidence during folding generates growth stratal patterns that are distinct from normal buckling (contrast Figs 6d and e), as identified by Oveisi et al. (2007) in their modelling of deformed marine terraces along the frontal folds of the central Zagros.

In summary, the vertical motion of synclines relative to their "regional" is not controlled by the folding mechanism, as proposed by Groshong (2015), but the ductility of the deeper parts of a deforming stratigraphic section. The distinction between detachment folding and buckling on these grounds is false.

The Incahuasi anticline as a buckle fold

In the oil and gas industry, the effectiveness of structural interpretations on the scale of cross-sections is repeatedly tested by drilling. However, being commercially sensitive, interpretation failures are rarely reported. An honorable exception is Total's development history of the Inchuasi structure in the SubAndean fold belt of Bolivia (Heidmann et al. 2017; Fig. 7).

The target for exploration drilling has been the porous sandstones of the Huamampampa Formation (Devonian) that host major gas reserves. These underlie the Los Monos Formation (Devonian), a shale-prone unit that forms a top-seal. It also acts as a ductile unit across which deformation changes (e.g. Rocha and Cristallini 2015, and references therein). The overlying Carboniferous to late Cretaceous units appear to deform as a single competent beam. At outcrop these strata form a fold-belt with remarkable lateral continuity of anticline hinges (>200km) separated by synclines that host Tertiary syn-kinematic foredeep sediments (Fig. 7a). The Huamampampa Formation lies at the top of a Silurian-Devonian package that is generally assumed to deform as a single unit, detached from the underlying basement along the Upper Silurian Kirusillas shales. Prior to Total's drilling campaign there had been various attempts to forecast subsurface structure of the fold-belt using analogues models (e.g. Leturmy et al. 2000; Driehaus et al. 2014; Darnault et al. 2016), generally preconditioned to create a two-tier thrust system decoupled along the Los Monos Formation.

Two-tier deformation formed the initial subsurface model for Total's drilling (Fig. 7b). The target was the crest of a proposed hangingwall anticline in the underlying thrust system. However, this first well penetrated a faulted anticline and was terminated in Cretaceous strata on the western limb of the fold. In the light of this result, the structural interpretation was modified (Fig. 7c) and a side-track well proposed to target the deeper structure. As this side-track was drilled, rather than encounter the Huamampampa Formation in the crest of a simple anticline, these sandstones were found to be faulted and locally over-turned. Consequently, the structural interpretation was modified again (Fig. 7d).

The history of iterative subsurface interpretation and drilling on the Incahuasi structure is interesting. As knowledge was gained, the role of the Los Monos Formation as a significant zone of structural decoupling reduces. At the start of the drilling campaign the Carboniferous-Cretaceous upper stratigraphic beam is interpreted to be entirely decoupled from the Silurian-Devonian beam below and each has its own structural style. By the end of the campaign, the

Huamampampa Formation is interpreted as folded, broadly in harmony with the upper beam. A further detachment horizon, located within the Icla Formation, has been incorporated by Heidmann et al. (2017) so that the older Devonian and Silurian strata can shorten by simple fault-bend folds. But does the structural style need to vary with depth, from buckle folding at shallow levels and fault-bend folding at depth?

The Incahuasi anticline is re-assessed here using some buckling concepts (Fig. 8). This new interpretation has been balanced, so that all formations show the same horizontal contraction. The upper units of Carboniferous to Cretaceous age are illustrated as acting as the control unit (in the sense of Price and Cosgrove 1990). Rather than interpret the Los Monos Formation as a mechanical detachment (c.f. Heidmann et al. 2017), we suggest that it represents a transitional strain zone across which there is broad structural continuity. The underlying Devonian and Silurian strata are also shown to fold harmonically with the upper units, with localized accommodation faulting in the anticline hinge. It is these faults that were encountered as the sidetrack well entered the Huamampampa Formation. The fold may also continue below this unit too, so that the whole stratigraphic pile deforms as a single entity.

Our model differs from that of Heidmann et al. (2017). We suggest that the older Silurian rocks are not involved in the Incahuasi structure and there is a décollement surface within the lower Devonian rocks (Icla Formation) beneath the Huamampampa reservoir unit. This version conserves the cross-sectional areas of different formations between deformed and undeformed states (achieves formational area balance). It is possible that the deeper Silurian strata are involved – especially if deformation in these deep levels was largely homogeneous layer-parallel shortening. Testing this interpretation requires knowledge of the "regional" for the various stratigraphic units in the Incahuasi structure. The long section in Fig. 7a provides some insight. The base of the synclines in the upper beam of Cretaceous and younger strata, the lower enveloping surface of the folds, inclines gently west. However, if there has been deformation in the underlying Silurian and Devonian strata, this enveloping surface does not constitute a "regional". Information is needed for deeper basement trends and the position of horizons in the foreland – information that lies beyond the scope of even the long section reproduced in Fig. 7a.

If the Subandean fold and thrust belt of Bolivia, incorporating the Incahuasi anticline, are best considered as a train of buckle folds, we can apply the concepts of fold amplification of Casey and Butler (2004, Fig. 2e). Erosion of the anticline fold crests could have a critical influence on the amplification and tightening of folds, allowing deformation to progress beyond the expected lock-up interlimb angle (as shown in the analogue experiments of Dixon and Liu 1992; Fig. 5b). In contrast, sedimentation in the synclines could inhibit the growth of further anticlines between the existing folds, enhancing those structures that had already formed.

Cyclic folding and faulting – the Livingstone anticlinorium

Kink-band folding, accommodated by flexural slip, is the generally-accepted mechanism for the formation of structures in the foothills of the Canadian cordillera (Dahlstrom 1970). Tight kink anticlines in the hangingwalls to thrusts are conventionally interpreted as fault-propagation folds that have evolved and been carried by the thrust. Cooley et al.'s (2011) interpretation of the Livingstone anticlinorium of the foothills of the Canadian cordillera (Fig. 9) challenges this notion. The anticlinorium is a composite array of folds associated with the Livingstone Thrust. The strata are dominated by well-bedded Mississippian carbonates typical of this part of the Alberta foothills. Cooley et al. (2011) mapped the folds and, supported by detailed fracture studies and diagenetic histories of vein fills, deduce the deformation history. The Central Peak anticline initiated at depth, in parallel to the growth of the Livingstone Thrust. In this sense, it is a thrust-propagation fold. However, the anticline tightened after the thrust had accumulated its displacement. The structure has a two-stage history.

The history of the Livingstone anticlinorium contrasts with the idealized evolution of fault-propagation folds. The results of Cooley et al. (2011) indicate that deformation need not evolve as a simple passage from distributed folding to localized thrusting but rather it can cycle between these different localization behaviors. Similar patterns have been deduced for fold-thrust complexes in the French Subalpine chains (e.g. Butler and Bowler 1995). Interacting folds and thrusts are also modelled numerically by Jaquet et al. (2014). Cycling between localized thrusting and distributed folding has important implications for some hydrocarbon systems as it could change the timing of the development of fractures in prospective subsurface reservoirs relative to the timing of hydrocarbon charge. It could also compromise the integrity of seals.

3D folding – the nucleation problem.

Early work on analogue materials demonstrated that buckle fold trains can initiate on pre-existing heterogeneities (Dubey and Cobbold 1977). This notion can be explored using the folds of the Subalpine chains and Helvetics of the NW Alps. Structures are developed in the multilayer of thick Mesozoic platform carbonates interbedded with shale-prone formations (Fig. 10). The youngest carbonate platform, termed the Urgonian limestone (Hauterivian-Barremian) forms regional folds with hinge lines that can be traced over tens of km (e.g. Ramsay 1989). Folding in the Urgonian is apparently out-of-phase with structures in the underlying units, for example the competent Tithonian limestones (Fig. 10). In the Subalpine fold belt, two formations are separated by thick lower Cretaceous shales. Jurassic strata below the Tithonian limestone are also shale prone and thick. These stratigraphic successions are inherited from a Mesozoic basin section. In contrast, to the west the fold-thrust belt involves an interbedded succession of thick platform carbonates and thin shales. Consequently in this western area the stratigraphy deforms harmonically and the role of major buckling appears to be less important (Fig. 10; see Butler et al. 2018, for further discussion).

Within the Subalpine system, anticlines in the Urgonian limestone at several locations coincide with pre-existing normal faults. Two examples are shown here, from either end of the system. In the Vercors, a single east-dipping normal fault can be reconstructed from the folded Urgonian (Fig. 11a; Butler 1987). At the Col de Sanetsch in the Helvetic Alps of Switzerland, the Urgonian limestone is folded into a NW-facing fold pair. It contains arrays of SE-dipping normal faults that are onlapped by Tertiary strata deposited before folding (Fig. 11b). In both of these cases the normal faults have throws that are less than the thickness of the Urgonian limestone. Nevertheless, it is tempting to suggest that these pre-existing faults were sufficient to nucleate folding. Presumably the folds propagated laterally from these inherited flaws in the Urgonian beam to create the connected fold trains of the Subalps, as modelled in von Tscharner et al (2016).

Figure 12 is a hypothetical illustration of fold nucleation and growth. Isolated arrays of small normal faults, equivalent to those illustrated in Fig. 11, were developed before folding. They act as perturbations, in the sense of Dubey and Cobbold (1977) to nucleate early fold growth (Fig. 12b). As layer-parallel shortening continues, some of the folds amplify and propagate their hinges laterally – eventually to connect into a continuous fold train (Fig. 12c). This raises an important issue when considering an individual cross-section through a fold-belt. Explanations of the spatial distribution of specific folds or structural styles may lie outside the cross-section or structure of interest. A holistic consideration of the fold-thrust belt may be more informative.

<u>Implications for modeling strategies</u>

There have been various attempts to mimic the fold patterns of the Subalpine and Helvetic Alps (e.g. von Tscharner et al. 2016). These represent a considerable advance on approaches that impose a kinematic model to a multilayer to reproduce deformation within the Urgonian limestone (e.g. Smart et al. 2012). in that they are three dimensional. They do however use flawless rheological beams. Yet, if the results from analogue models of Dubey and Cobbold (1977) are generally applicable, buckle fold clusters nucleate on perturbations thus the initial fold pattern will develop from the amplification of these pre-existing heterogeneities. It is only at rather significant bulk contraction (>35%) that the fold system self-organizes with dominant wavelengths controlled by layer-thicknesses. If taken into the natural world, this implies almost all foothills systems are still under the influence of their heterogeneities. Perhaps the deformation of sedimentary multilayers is comparable to mineral physics – it is the existence of lattice defects that allows crystals to deform plastically (e.g. Nicolas and Poirier 1976, p. 52).

Comparing approaches

The folded Mesozoic strata of the Jura mountains of Switzerland were interpreted by Buxtorf (1916), largely using outcrop, well data and then-new railway tunnels. His cross-section (Fig. 13) shows variations in deformation localization, while retaining a common feature of decoupling of the cover rocks from the underlying basement. In this regard, his cross-section is similar to those considered by Dahlstrom (1970) in the Canadian foothills. Both view the deformation as thin-skinned. Buxtorf's interpretation of the structure beneath the Grenchenberg tunnel (Fig. 13) is amongst the most widely reproduced in structural geology. This section and its subsequent reworking was much cited as an example of buckle folding above a basal decoupling surface (e.g. Ramsay 1967). Subsequently it has become a much-cited example of detachment folding, featuring in text books such as Fossen (2016). Likewise, the various other fold-thrust models illustrated in Figure 1 all have long heritage. Fault-bend folds (Fig. 1a) were famously interpreted in the Appalachians by Rich (1934). The notion that thrusts grow as strain localizes in folded strata, the feature of fault-propagation folding (Fig. 1b; Williams and Chapman 1983), goes back to at least to Willis (1894) and Heim (1878). However, since the early 1980s, although these historical roots are often cited, the descriptions of structural geology surrounding them, have become blurred. Thus, the now-prevalent terminology of fault-related folding, outlined on Fig. 1, has been increasingly used to develop structural interpretations, without addressing underlying issues, especially concerning buckling instabilities and distributed strain.

<u>Evolving literature and confirmation bias</u>

Figure 14 charts the increase in the application of idealized fold thrust geometries as depicted on Fig. 1, from the early 1980s to the present. It also shows the publication of research on buckle folds, sourced from the online tool Scopus - Elsevier's abstract and citation database, for the same period. Cursory inspection may suggest that, if the literature reflects geological reality, the dominant style of deformation is detachment folding and that there are relatively few buckle folds. What are the implications of this? Are detachment folds distinct from buckle folds? Are true buckle folds rather rare? Can cross-sections across mountain belts like the Jura be reliably constructed using simple methods and folding concepts (e.g. Poblet and McClay 1996; Mitra 2003; Shaw et al. 2005)?

We argue below that the distinction between detachment folding and buckle folding above a décollement is false. Hence, much of the literature represented in Fig. 14 simply follows the newer categorization of detachment folds, as part of the fold-thrust belt model suite, rather than buckle folding. The effect is to polarize structural geologists and risks detaching those engaged in subsurface interpretation from a rich vein of knowledge.

The use of categorization of concepts and associated nomenclature can be useful standard scientific practice to aid communication and to share analogues. Applications include fossils (e.g. Woodward 1885), plants (e.g. Jones and Luchsinger 1979) and minerals (e.g. Morimoto 1988; Leake et al. 1997). Grouping in this way generally implies associations within categories and is appropriate when these objects are similar. However, the approach can promote studies that seek to confirm existing understanding at the expense of those that seek to challenge conventional wisdom. This is termed "confirmation" bias, unwitting selectivity in the acquisition and use of evidence (Nickerson 1998), which is compounded by the availability of models - "availability bias". These type of bias are widely recognized in scientific investigations (e.g. Mynatt et al. 1977) and can restrict the range of concepts or models chosen to explain natural phenomena. Alcalde et al. (2017) show the impact of a limited range of training examples on interpretations of a fault in a seismic image. If the findings of this paper are generically applicable, today's structural geology students, brought up on a diet of post 1990 text-books and sub-surface interpretation manuals, will invariably interpret structures such as those on Buxtorf's cross-sections through the Jura (Fig. 13) as detachment folds and name them as such, rather than consider them to be buckle folds. It is perhaps unsurprising therefore that examples of natural structures or their interpretations illustrated on cross-sections that conform to the specific styles illustrated in Fig 1 are widely documented. Alternative approaches and observed structural geometries may be under-reported or poorly cited in published literature. Such bias is increased by reliance on modeling software that only allows for a narrow range of deformation modes for cross-section construction (Groshong et al. 2012). Perhaps the reliance on simple kinematic descriptions of fold-thrust complexes charts the increasing use of seismic reflection data to construct cross-sections through the subsurface. In this context, conventional structural interpretation strategies emphasize beds, the continuity of stratal reflectors and their offsets across faults (but see Iacopini and Butler 2011).

So consider this rationale: fault displacement and bed-length can be measured and sections constructed and restored accordingly; deformation distributed strain cannot be readily detected or quantified; therefore the possibility of strain is ignored; so bed deformation is assumed to have occurred by concentric folding alone. The resultant cross-section is restorable and thus is assessed as carrying a low risk of being wrong, certainly compared with unrestored interpretations. But this risk assessment would rely on arbitrarily negating the significance of distributed deformation and focusing exclusively on interpretations that are restorable using purely concentric folding and fault slip. As such it is unreliable.

The above scenario is an example of the McNamara Fallacy, a form of cognitive bias that engenders over-confidence in a particular deduction (e.g. Bass 1995). It is a widely recognized syndrome resulting from over-reliance on a narrow range of data, generally the most-readily quantitative, at the expense of factors that are less amenable to quantification (e.g. Martin 1997; O'Mahony 2017). In our scenario, the bias lies in retaining only a narrow range of possible structural geometries and relegating others as being irrelevant complexities - only adopting modeling solutions that follow a few numerical approximations while ignoring interpretation possibilities that cannot be so simply modelled. The challenge then is to increase the availability of models and approaches, rather than rely on a narrow, over-defined set of possible solutions.

Localisation – forced folds vs buckle folds

Here we develop a broader basis for understanding relationships between folds and thrusts, linking the idealized fold-thrust models (Fig. 1) to buckle fold concepts (Fig. 2). Our aim is to provide a more holistic view of deformation, and deformation localization in compressional settings that better considers the true structural evolution of folds, faults and their interplay in multi-layered stratigraphy. Notwithstanding the issues raised above, we restrict discussions here to cross-sections, but recognize the importance of adopting 3D approaches for understanding structural evolution (but see Butler 1992).

Consider layer-parallel contractional deformation acting upon a sequence of parallel-bedded strata (Fig. 15). We can chart the distribution of deformation within an individual layer with respect to the aggregation of shortening. For ideal fault-bend folding, a fault nucleates instantly so deformation is localized onto an infinitesimal small part of this layer. As shortening increases displacement remains entirely localized (Fig. 15). Note that in the hangingwall to the fault, the layer is deformed, simply as a consequence of displacement. Fischer and Coward (1982) quantify these flexural flows. As Cosgrove and Ameen (1999; following Stearns 1978) note, this is an example of *forced folding* – a consequence of displacements in the surrounding rocks. They draw distinction between folds formed as a consequence of compression acting parallel to layering – *buckles*. In these systems a single horizon never localizes a thrust ramp but simply, the strata above the detachment, décollement, or thrust flat continues to accommodate deformation by folding. If the layer retains constant thickness during deformation, folding in that layer must be accommodated by rotation and, as noted previously (Butler 1992), if there is a fixed décollement surface, there must be hinge migration. Consequently, the amount of rotated bed must increase as shortening is accommodated (Fig. 15). Williams and Chapman (1983) developed a general strain case so that layer thickness can change during deformation.

We can consider the two behaviors discussed above to represent end-members (Fig. 15) – either: (i) instantaneous displacement localization or (ii) distributed folding continuing through the entire deformation history. However, fault-propagation folding envisages deformation evolving so that a layer first deforms by folding but then localizes displacement as a thrust grows into it (see

Mitra 2003 and many others). This chronology may be an expression of strain hardening. But the universal relevance of this model is challenged by the study of Cooley et al. (2011) discussed above (Fig. 9). Folding happened both before and after movement on the Livingstone Thrust.

The concept of mechanical stratigraphy is used by some to assess strain development (especially fracture patterns) assuming larger-scale structural geometries and evolutions that build upon concepts of fault-related folds (e.g. Smart et al. 2012; Hughes et al. 2014). Using the terminology of Cosgrove and Ameen (1999) – these are effectively viewed as forced folds as distinct from buckles. This view is reinforced by contributions from Groshong (2015). The implication is that buckling is a rare process in fold-and-thrust belts. Yet buckle folds and forced folds have different mechanics and yield different forecasts of fracture and other strain patterns (discussed by Cosgrove and Ameen 1999). Failure to consider buckling processes will make inappropriate fracture forecasts, of structurally controlled fractures.

Discussion: where have all the buckles gone?

For decades, most studies of fold-thrust belts have considered folding to be a consequence of thrust geometry and faulting processes. The implication is that layer buckling is a rare process in fold-and-thrust belts. We have argued here that this is wrong – and that there is a spectrum of folding and faulting styles that can co-exist in stratigraphic multilayers. To answer our titular question: the buckles are still there. In many studies over the past 25 years, structures which have involved components of layer buckling have simply been renamed as fault-propagation or detachment folds. But through renaming, swathes of relevant knowledge on buckling systems has been largely neglected, not only by communities striving to interpret and forecast the subsurface, but also by those attempting to down-scale to forecast patterns of fracture and strain within folds.

The use of restricted structural styles in cross-section construction was strongly criticized by Ramsay and Huber (1987; p. 557), although wrongly conflated with the concept of section balancing. Simplification is an inherent process in most scientific investigation – its appropriateness depends on the specific problem under investigation. So the reasons for adopting particular geometric solutions depend on the purpose of a particular cross-section or modeling campaign.

Ramsay (1967), in developing mathematical approaches to quantify the geometry of deformed rocks, focused on spatially continuous strain. Up-scaling emphasizes strain compatibility so that heterogeneous strains change gradually through a deformed rock volume. In contrast, the development of thrust concepts has emphasized discontinuous deformation and characterizes these discontinuities – the thrust faults. Up-scaling and the consideration of strain compatibility underpins the notion of section balancing. But by emphasizing displacement and the associated forced folds, the role of distributed strain and buckling have been neglected. Buckle folds and forced folds have different mechanics and yield different forecasts of fracture and other strain patterns (Cosgrove and Ameen 1999). There was once extensive research on strain patterns in thrust sheets (e.g. Coward and Kim 1981; Morley 1986; Woodward et al. 1986; Geiser 1988; Mitra 1994) that sought to quantify distributed deformation alongside thrust displacements. However, there are few such studies today.

The problem of over-confidence in structural interpretation is compounded by publications, as illustrated on Fig. 14 . As a structural geology community we should consciously challenge our interpretations that conform to 'classic' rules and geometries. In this way we may limit further bias in our interpretations of fold-thrust structures and cease contributing further to availability bias (Bond et al., 2007; Alcalde et al. 2017).

Interpretations biased from adopting Dahlstrom's "foothills family", and the derivative range of fold-thrust models (e.g. Shaw et al. 2005; Fig. 1), can be managed if the purpose is to up-scale from structural interpretations. This might be to evaluate tectonic processes through obtaining estimates of shortening of rocks in the upper crust, if quoted as minima, or a range of likely values rather than single determinations (e.g. Elliott and Johnson 1980; reviewed by Butler 2013). Or it could be to develop predictions of the large-scale thermal evolution of thrust belts (e.g. Deville and Sassi 2005; McQuarrie and Ehlers 2017).

However, understanding the evolution of folds, predicting smaller-scale structures within specific layers and forecasting their geometry in the subsurface, are hindered by considering only a narrow range of deformation modes. The history of exploration drilling for hydrocarbons in thrust systems bears testimony to these inherent uncertainties (Butler et al. 2018), as typified by our discussion of the Incahuasi structure (Fig. 7). Understanding the risks of interpretation failure and the construction of cross-sections that improve predictions of subsurface structure, may be enhanced by better integration both of information on the heterogenous localization of strain within layered sequences and of buckle folding concepts into fold-thrust models.

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Figure captions

Figure 1. Idealised fold-thrust relationships, modified after Jamison (1987).

Figure 2. A compilation of buckle fold concepts and results of analogue experiments. a) single layer buckle folding, with layers of increasing competence (1-5), with the matrix competence equal to that in layer 1 (modified after Ramsay 1967). b) the concept of contact strain, adjacent to a buckled single layer (modified after Ramsay 1967). c) numerical models of evolving buckled single layer (modified after Reber et al. 2010). d) result of an analogue multilayer model subjected to layer-parallel contraction that synchronously developed folds and faults (modified from a photograph by Price and Cosgrove 1990). e) evolution of stress-strain relationships during buckling, using the deformation history outlined by Casey and Butler (2004).

Figure 3. Complex fold-fault relationships. a) a faulted antiform hinge zone developed in turbidite sandstones, modified from a photograph by Price and Cosgrove (1990, fig. 12.26; their "accommodation faults'). b) Fold-related faulting. a) and b) illustrate idealized patterns of hinge-failure (Price and Cosgrove 1990) while (c) illustrates this behavior in nature. The figure is redrawn from a photograph from Price and Cosgrove (1990, fig 12.26). d) Subsurface interpretation of stacked thrust faults within the Ventura Avenue Anticline in California, modified after Mitra 2003, fig. 10). e) Subsurface interpretation of the Anschutz Ranch East Field in the Utah-Wyoming thrust belt, modified after Boyer (1986, fig. 16).

Figure 4. plan views showing the linkage of folds by lateral hinge-line propagation. a-b are redrawn from an analogue experiment using a plasticene multilayer by Dubey and Cobbold (1977).

Figure 5. Development of fold trains. a-b illustrates the evolution of a single experiment with increasing contraction, reported by Dixon and Lui (1992). c)

and d) show the results of finite element models of folding by von Tscharner et al. (2016).

Figure 6. Are detachment folds and buckle folds really different? a) and b) show Groshong's (2015) conceptualization of these styles, detachment folding and buckling respectively. c) illustrates one source of confusion, arising from cropped and centred images recording experiments on analogue materials - exemplified here, retraced from photographs in Cobbold (1975; wth additional annotations). The control layer (X) is encased in a lower viscosity matrix upon which was printed a passive grid (red lines) that chart the contact strain zone. One of the grid lines is identified here and correlated between deformation states (Y). The low strain state evolves into the high strain – shown here in Cobbold's framing (left side) and re-hung relative to the passive marker Y (right side). Note that the determining subsidence of synforms depends on the adopted reference frame – or "Regional". d) and e) illustrate results of Simpson's (2009) numerical modelling of fold-trains developed above a very low-viscosity decollement zone. The "Regionals" are determined using the undeformed section to the left side of each model.

Figure 7. The interpretation of the Incahuasi anticline in the Bolivian foothills, after Heidmann et al. (2017). a) simplified long cross-section through the thrust belt provided for context (simplified from fig. 8 of Heidmann et al. 2017). Total's evolving interpretation of the Incahuasi anticline with the acquisition of well data is shown in the remaining parts of the diagram (b-d; modified from fig. 15 of Heidmann et al. (2017). b) illustrates the pre-drill interpretation; c) shows a modified interpretation after the first well-bore; d) shows a final interpretation that incorporates information from the first well-bore and its side-track.

Figure 8. A reinterpretation of the Incahuasi structure as a buckle-folded multilayer – with continuity of the axial surface to depth. Contrast with the pre-drill interpretation and its evolution (Fig. 7b-d).

Figure 9. Evolution of fold and thrust structures in the Central Peak anticline in the Livingstone Range, Canadian Rocky Mountains foothills – modified after Cooley et al. (2011).

Figure 10. Interpreted cross-section through the front of the Bornes sector of the Subalpine fold and thrust belt of the French Alps (modified after Butler et al. 2018).

Figure 11. The nucleation of anticlines on pre-existing heterogeneities. These two examples come from the western Alps and show the Urgonian limestone (Hauterivian-Barremian) which is generally assumed to form a competent formation within an alternating series of limestones and shales (control bed in the sense of Price and Cosgrove 1990). a) interpreted cross-section from the Col de la Bataille, Vercors, France. b) annotated photograph from the Col de Sanetsch, Switzerland (visible cliff-height c 700m, to the summit of Spitzhorn).

Figure 12. Conceptual fold nucleation on pre-existing structures and the lateral propagation of fold hinge lines – shown here in plan view of the top of a control unit. a) shows the initial distribution of minor normal faults that will serve to nucleate the initial fold clusters (b). c) shows the lateral propagation of these hinge lines into previously unfaulted parts of the horizon. Considerations of cross-sections in these unfaulted areas would fail to identify the full causes of fold development.

Figure 13. Buxtorf's (1916) oft-reproduced cross-section through the Jura mountains of Switzerland, based on wells and railway tunnel.

Figure 14. A comparison of publication history of papers that cite the terms "fault-bend folding", "detachment-folding" and buckling/buckle folding. The sample was created by searching Scopus and filtering on papers classified as earth and environmental science. Papers are grouped into three-year bins.

Figure 15. Conceptual model for the different styles of fold-thrust structure outlined in Fig. 1, examining the pattern of distributed deformation (represented by the length of buckled bed), using the approach of Butler (1992). It illustrates the differences between “forced folding” (where deformation is solely localized on the thrust surface) and buckling. Only fault-bend folds are purely “forced” and thus only these folds are entirely fault-related. All other forms involve a component of buckling. Vertical scales refer to number of papers per 3-year bin, coded to the type of fold.

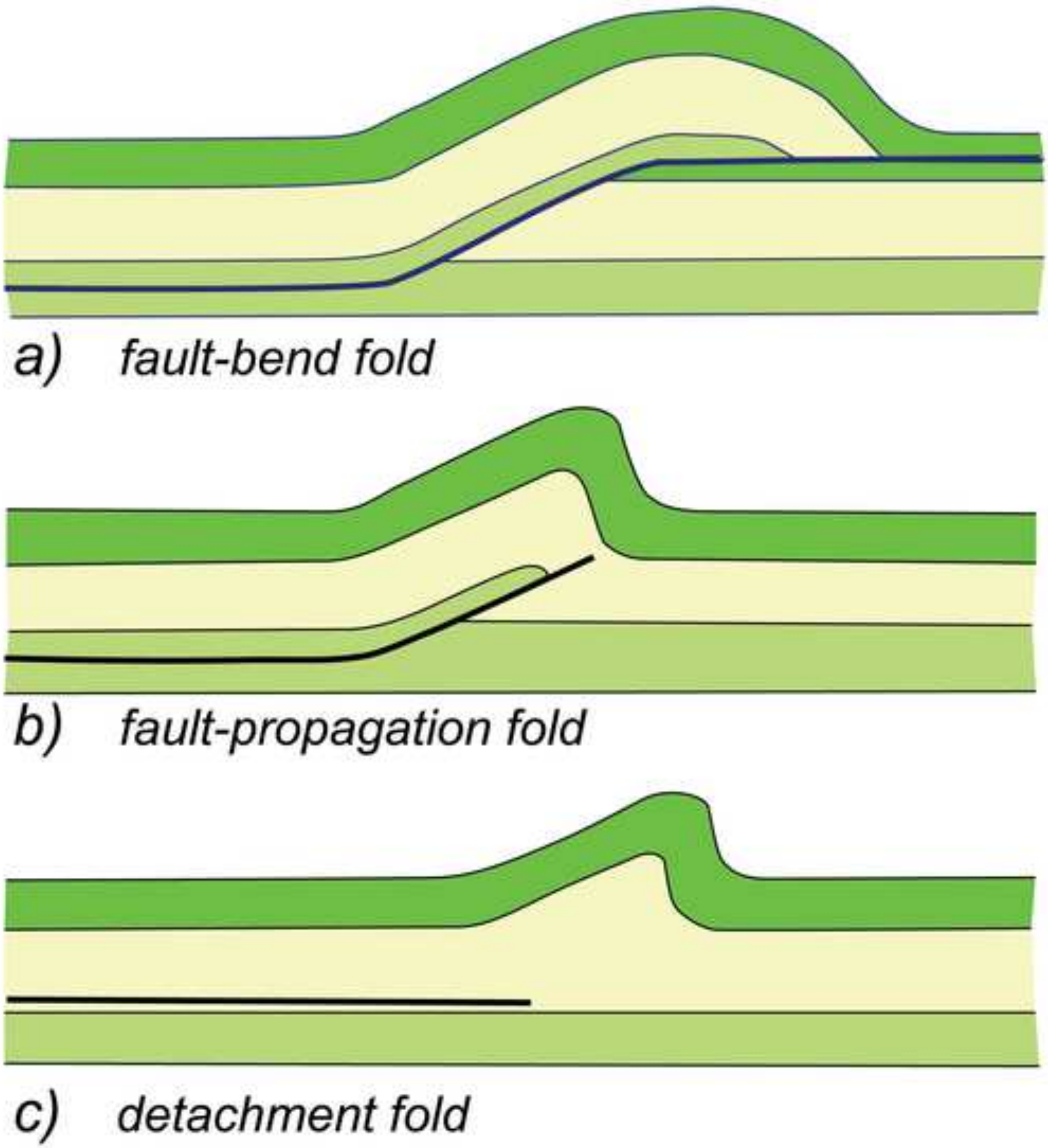

a) fault-bend fold
b) fault-propagation fold
c) detachment fold

Figure 2

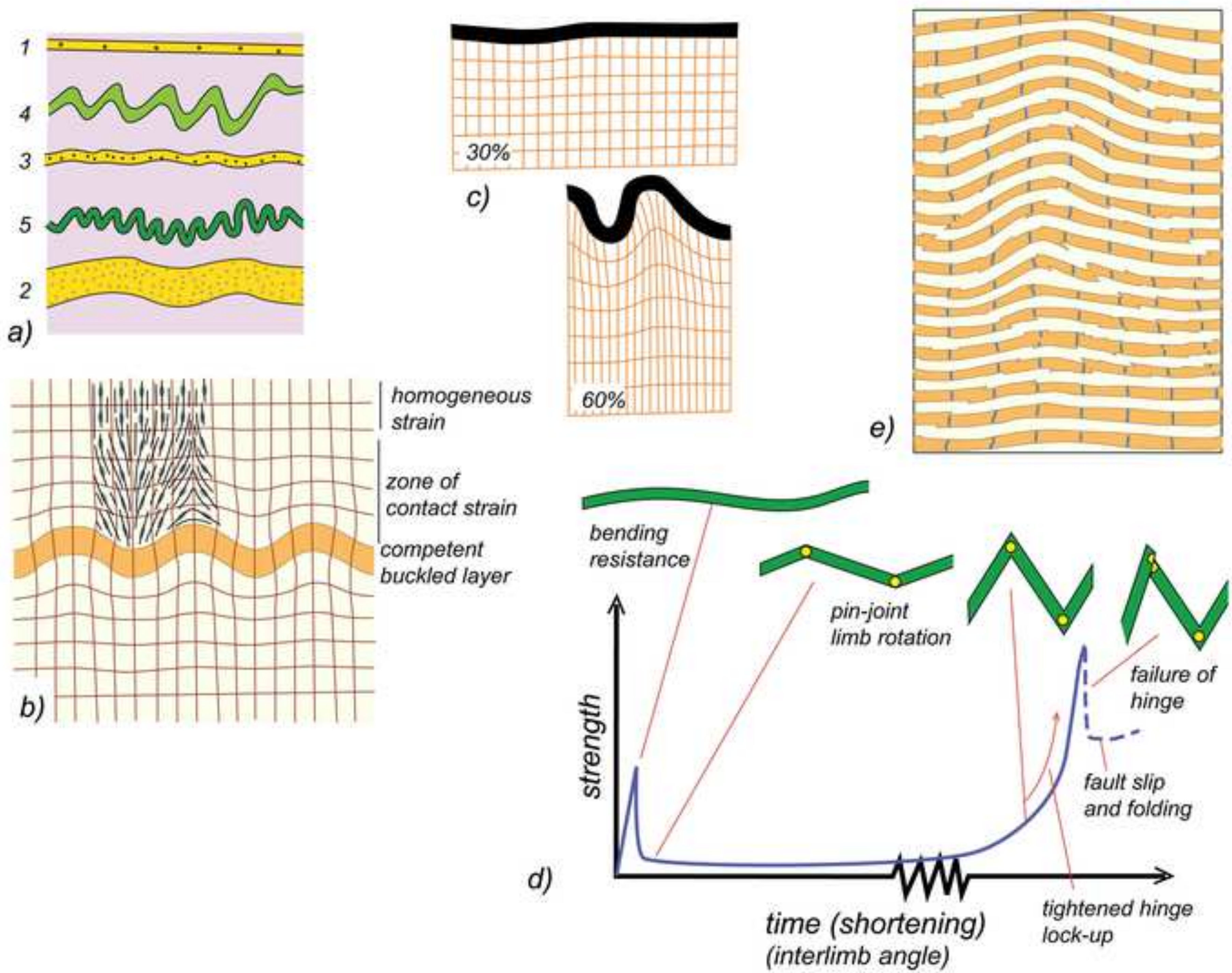

1
4
3
5
2
a)
c)
30%
60%
e)
homogeneous strain
zone of contact strain
competent buckled layer
b)
bending resistance
pin-joint limb rotation
failure of hinge
fault slip and folding
strength
d)
time (shortening)
(interlimb angle)
tightened hinge lock-up

Figure 3

Click here to access/download;figure;Fig 3 faulted folds.jpg

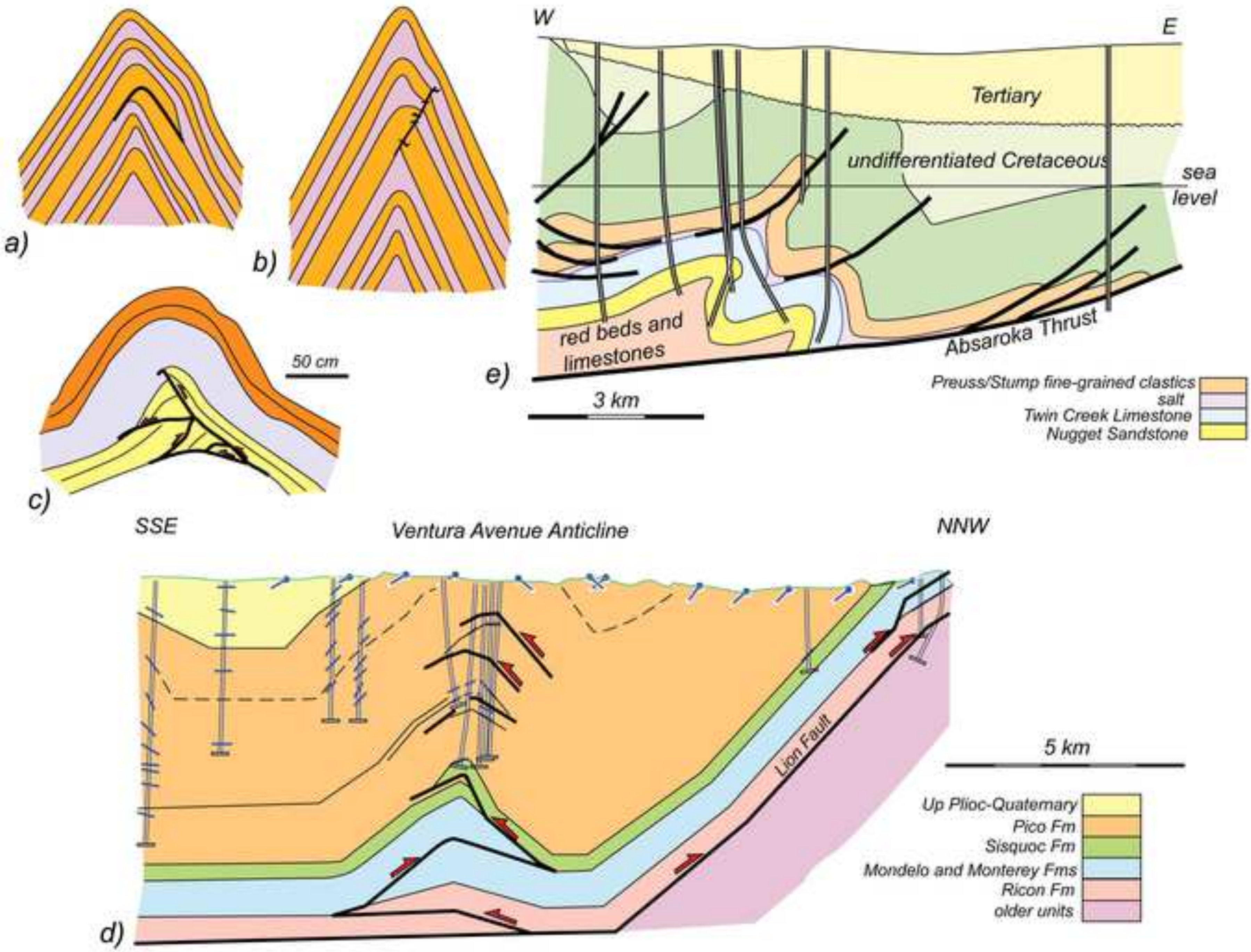


Figure 4

Click here to access/download;figure;Fig 4 hinge lines.jpg

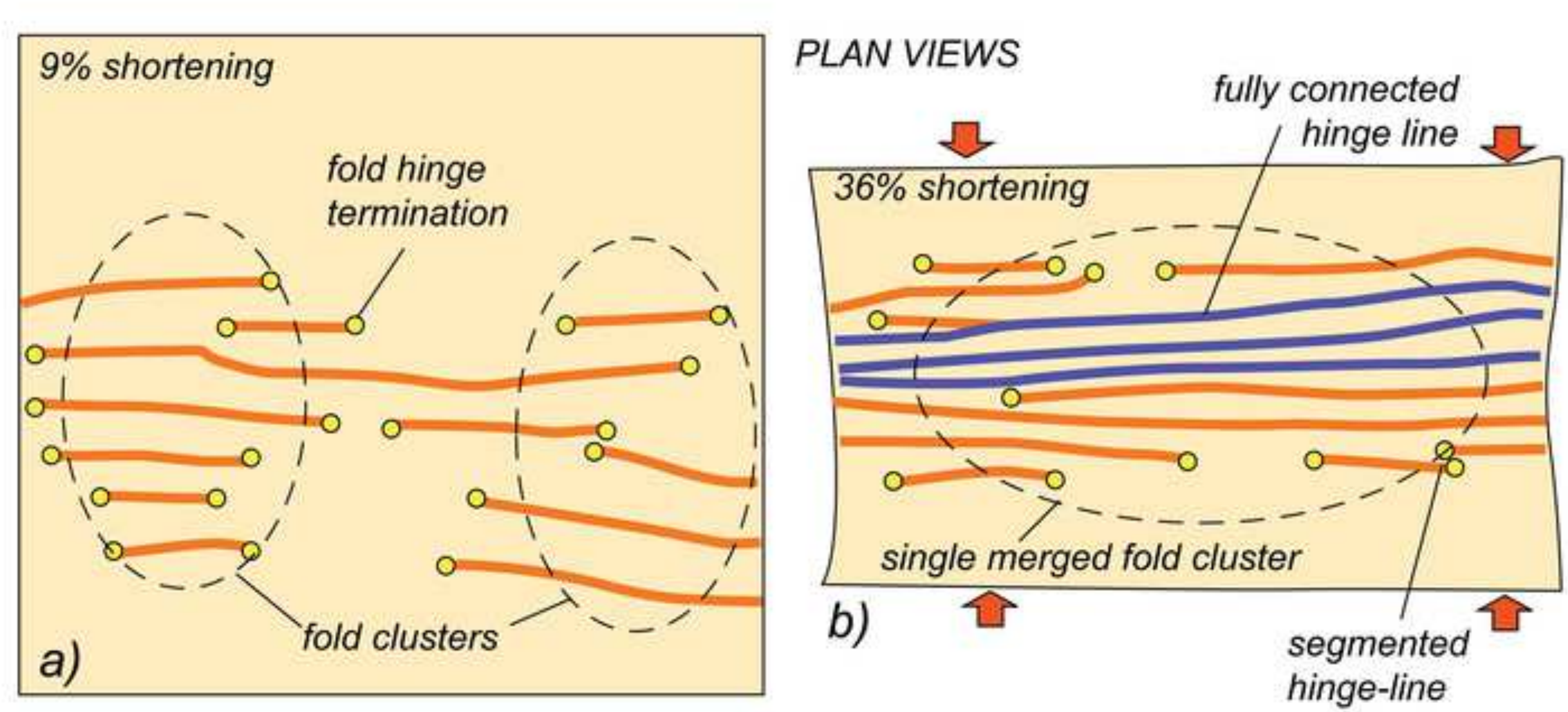


Figure 5

Click here to access/download;figure;Fig 5 multilayers.jpg

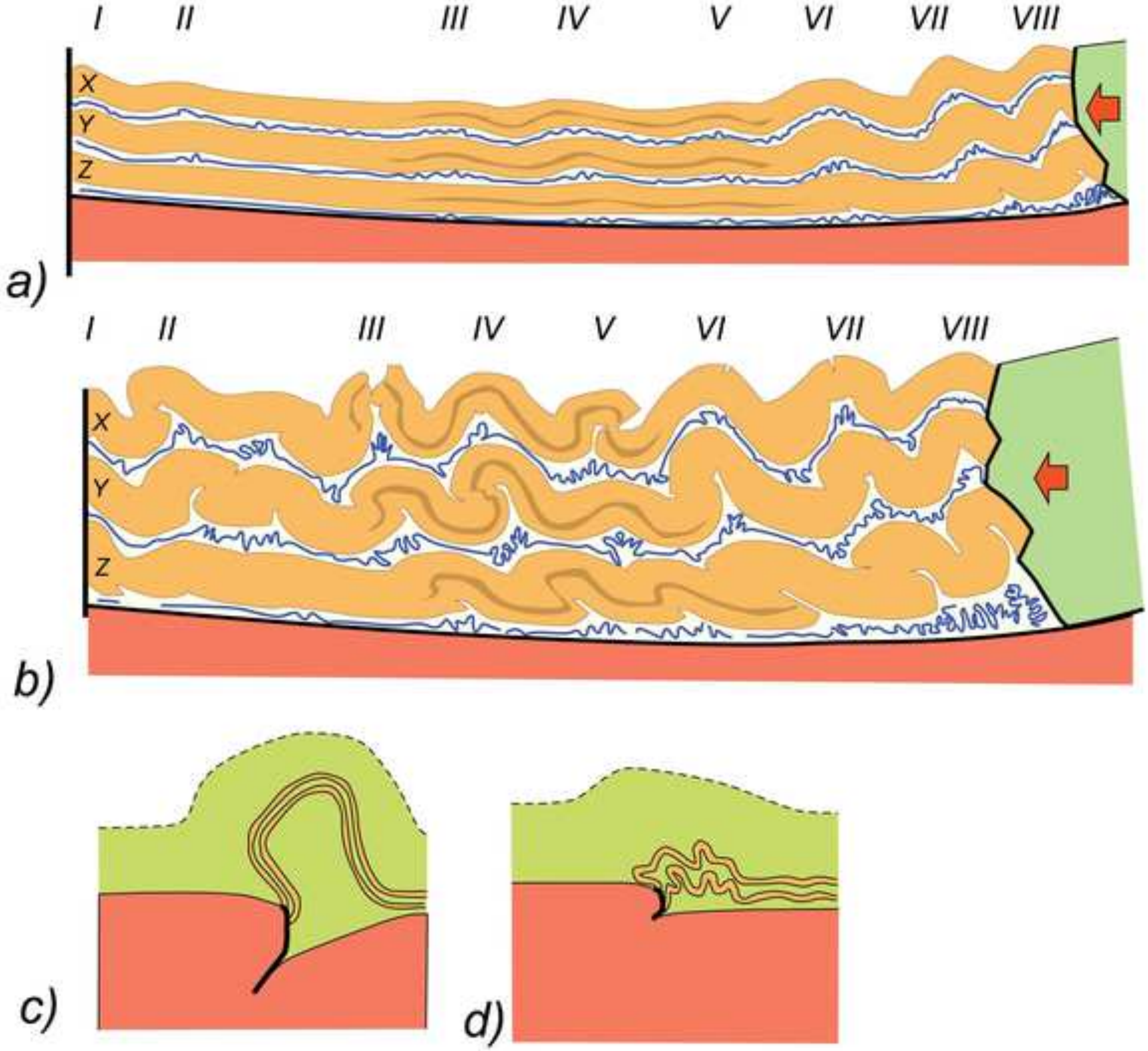
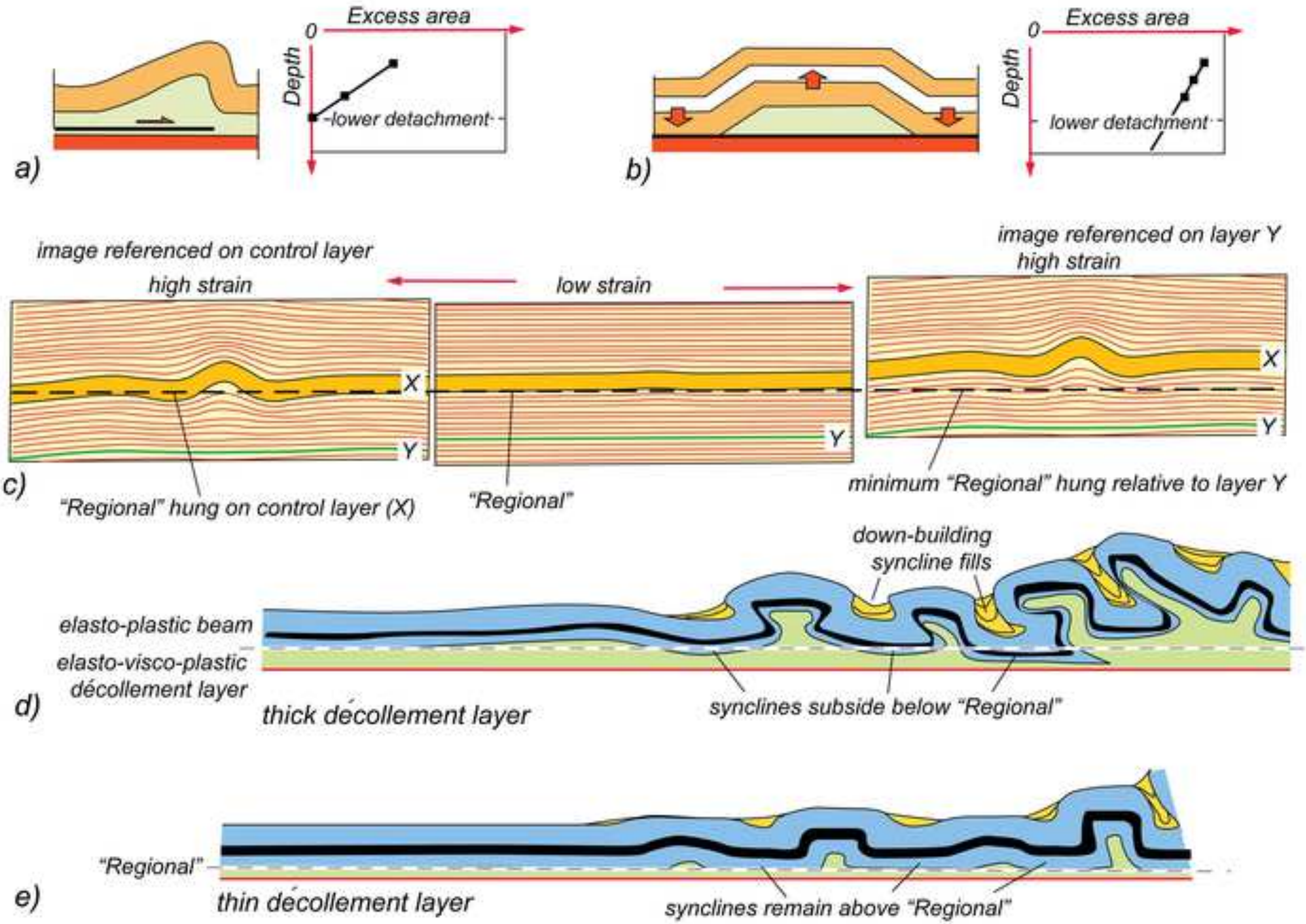
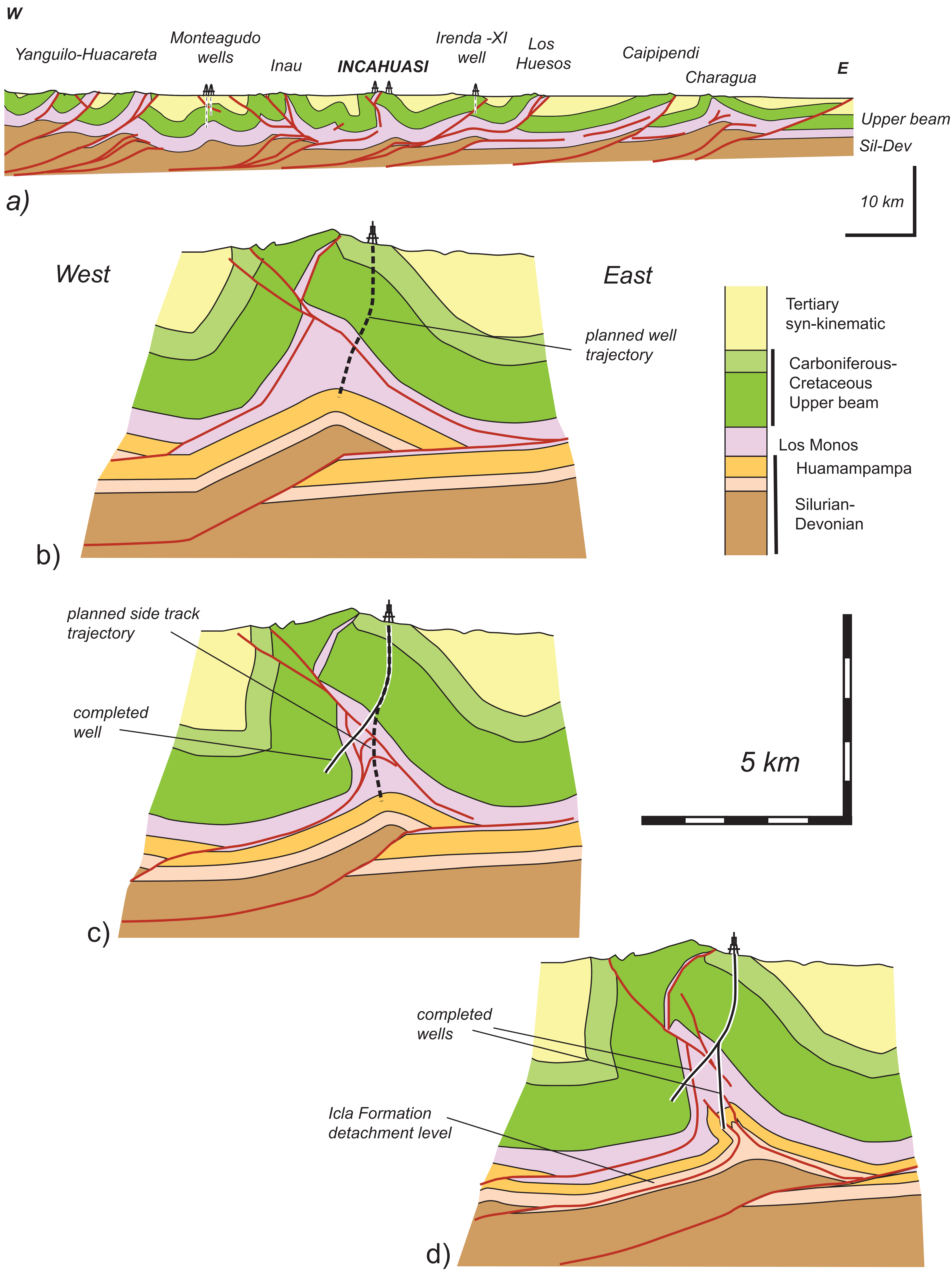


Figure 6 Click here to access/download;figure;Fig 6 buckle detachment.jpg




W
Yanguilo-Huacareta
Monteagudo wells
Inau
INCAHUASI
Irenda -XI well
Los Huesos
Caipipendi
Charagua
E
Upper beam
Sil-Dev
a)
10 km
West
East
planned well trajectory
Tertiary syn-kinematic
Carboniferous-Cretaceous Upper beam
Los Monos
Huamampampa
Silurian-Devonian
b)
planned side track trajectory
completed well
5 km
c)
completed wells
Icla Formation detachment level
d)

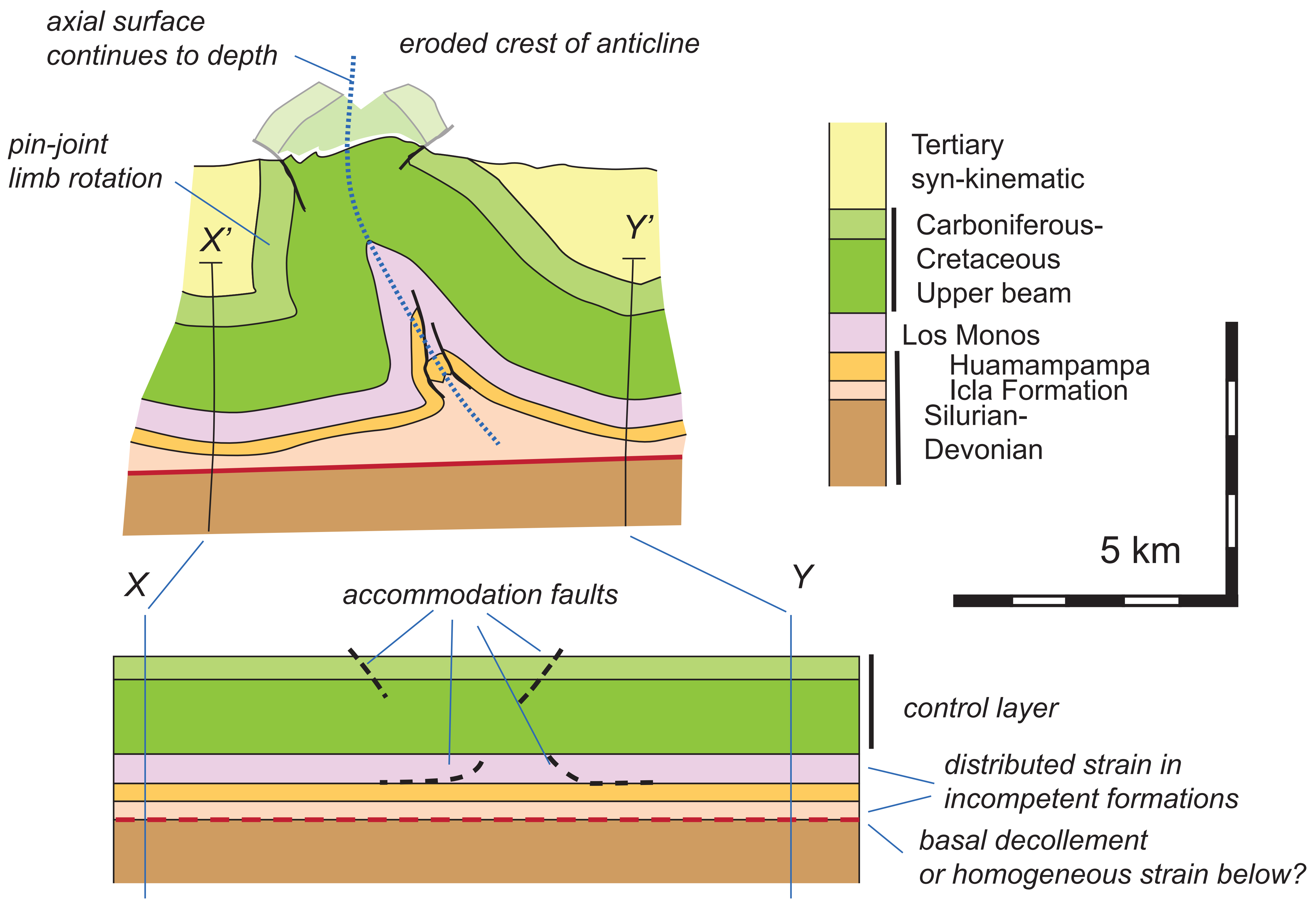

axial surface
continues to depth
eroded crest of anticline
pin-joint
limb rotation
X'
Y'
Tertiary
syn-kinematic
Carboniferous-
Cretaceous
Upper beam
Los Monos
Huamampampa
Icla Formation
Silurian-
Devonian
5 km
X
Y
accommodation faults
control layer
distributed strain in
incompetent formations
basal decollement
or homogeneous strain below?

Figure 9

Click here to access/download;figure;Fig 9 Cooley.jpg

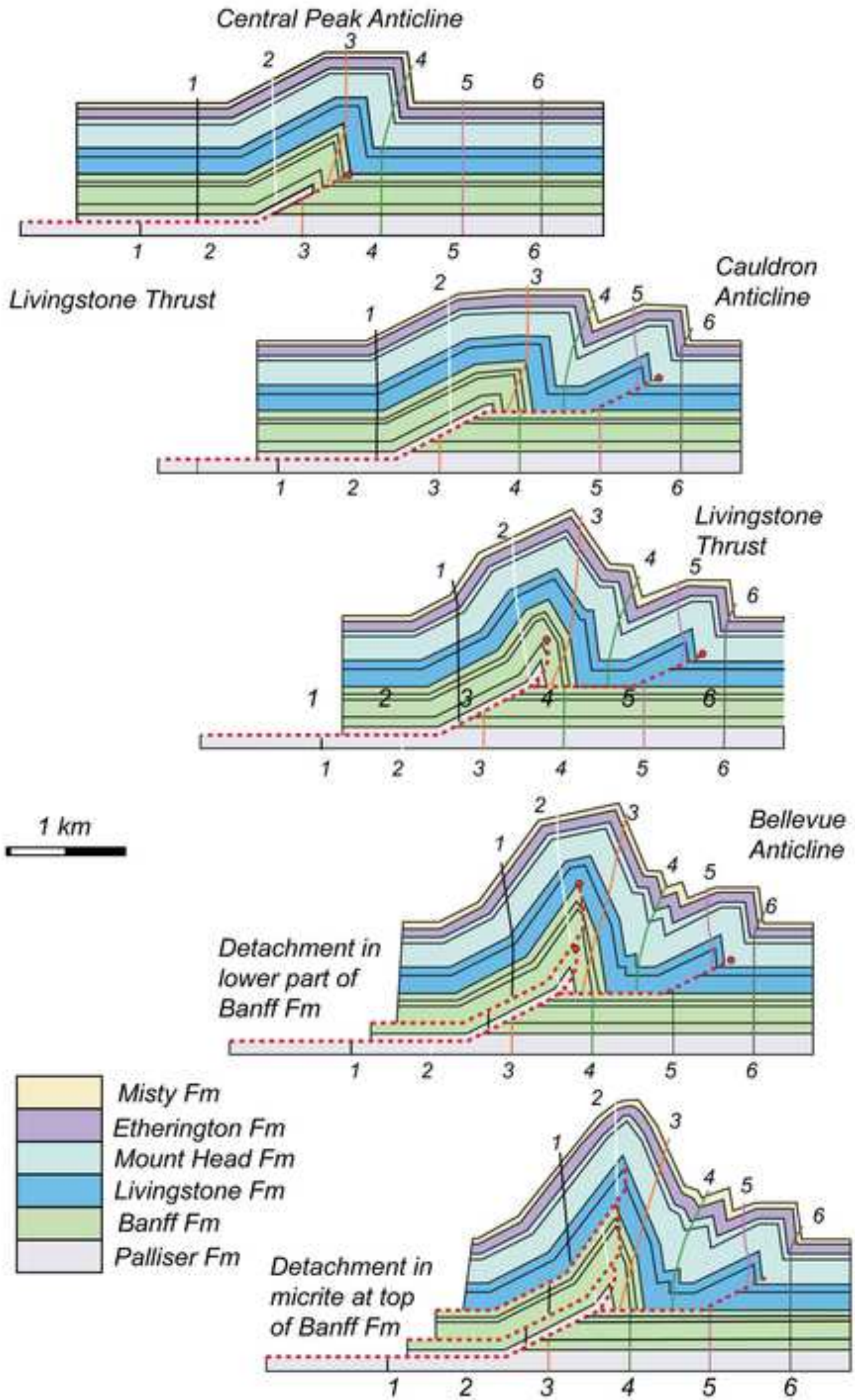


Figure 10

Click here to access/download;figure;Fig 10 Bornes section.jpg

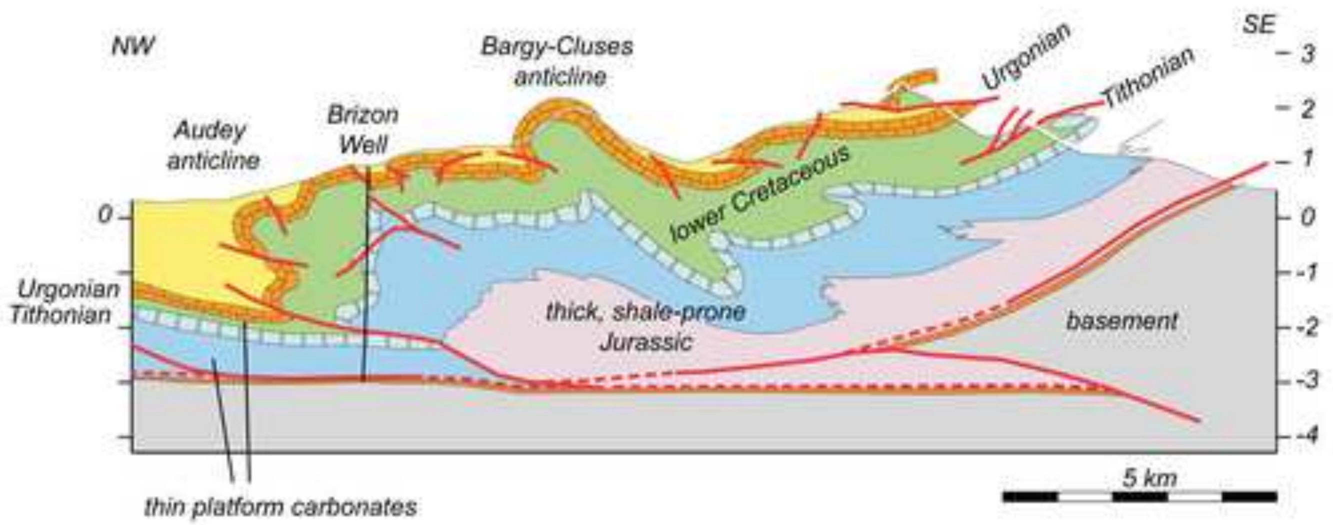
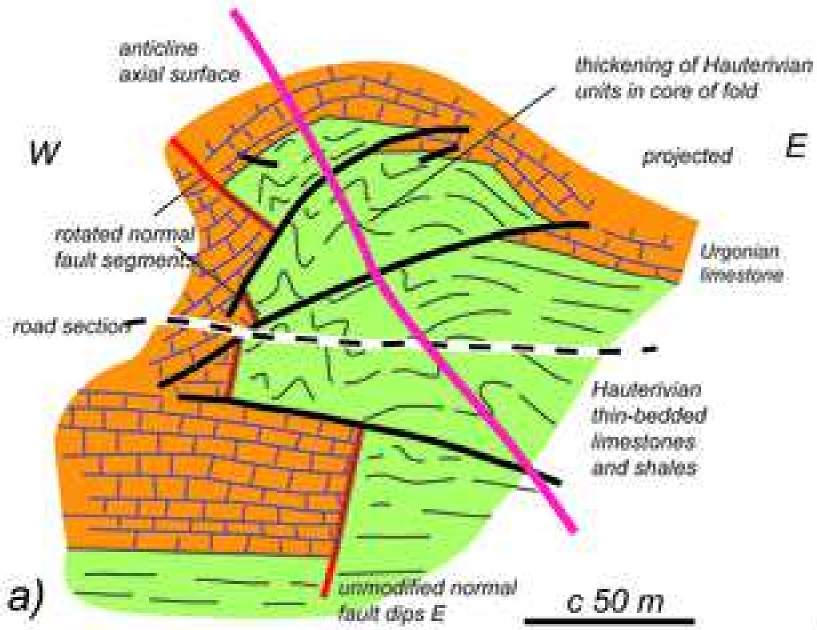


figure 11

Click here to access/download;figure;Fig 11 Urg folds.jpg



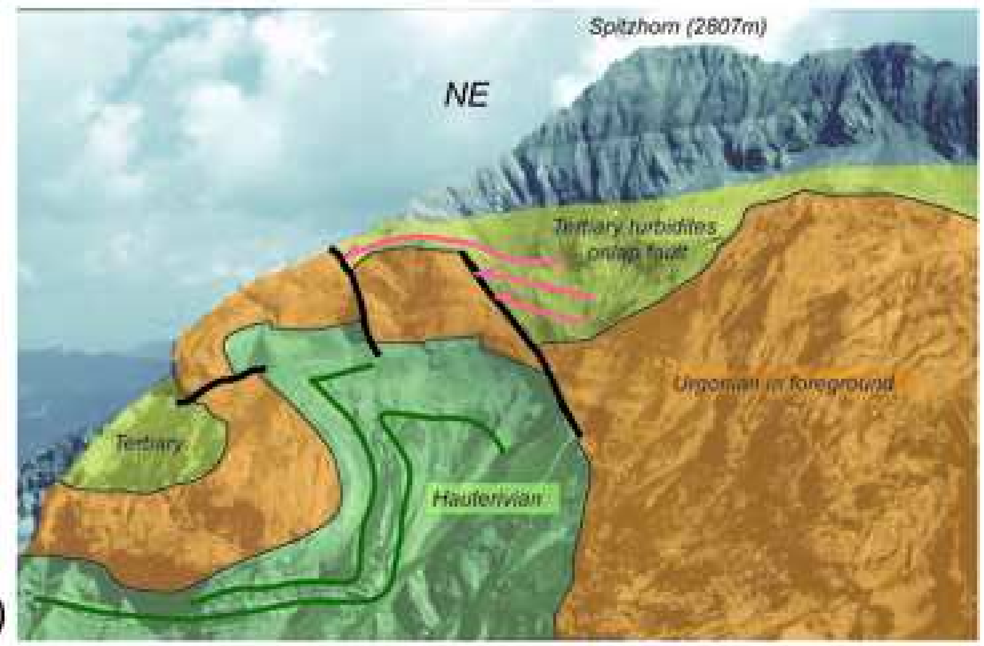


Figure 12

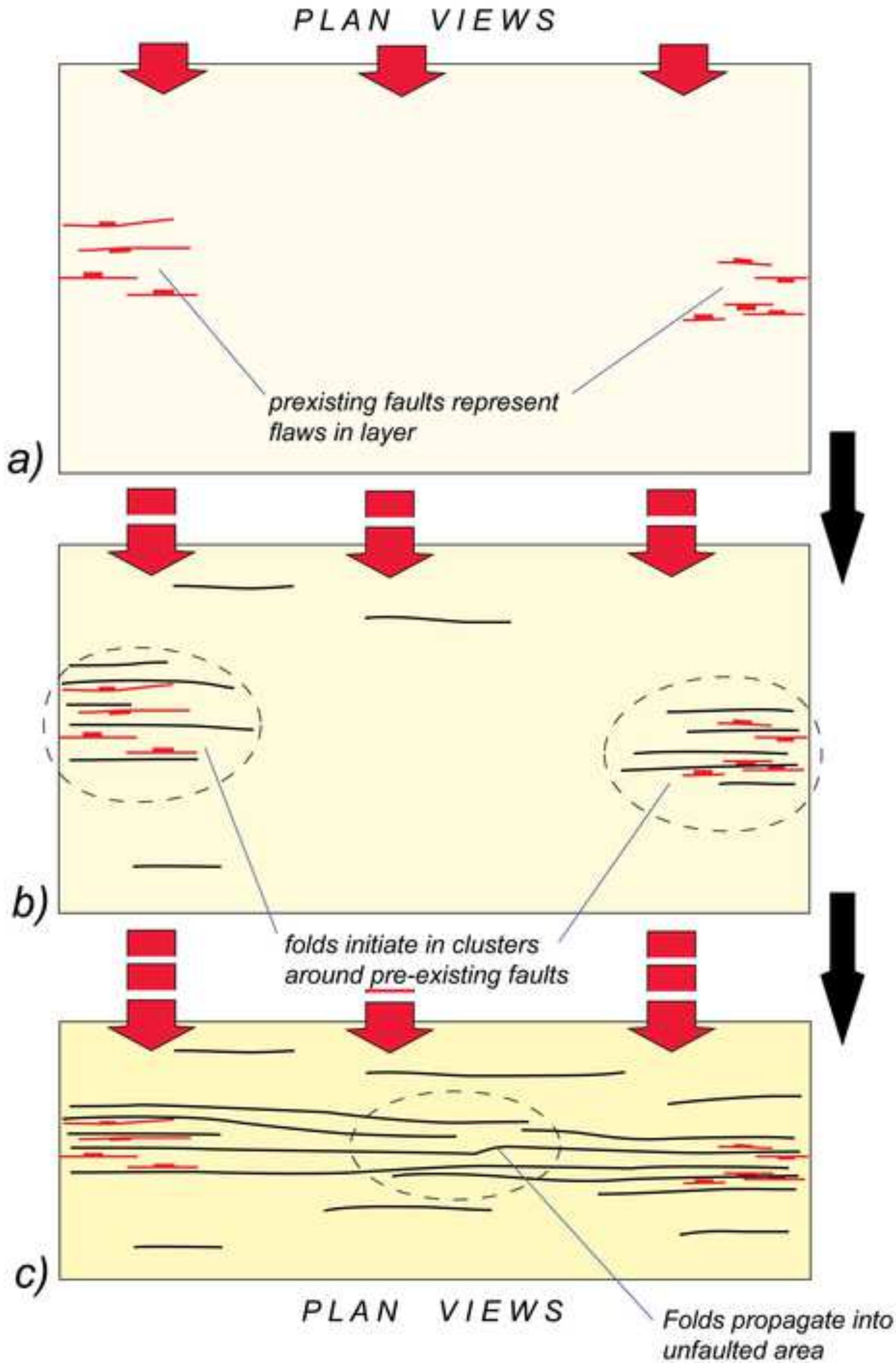

PLAN VIEWS
prexisting faults represent flaws in layer
a)
b)
folds initiate in clusters around pre-existing faults
c)
PLAN VIEWS
Folds propagate into unfaulted area

Figure 13

Click here to access/download;figure;Fig 13 Buxtorf buckles.jpg

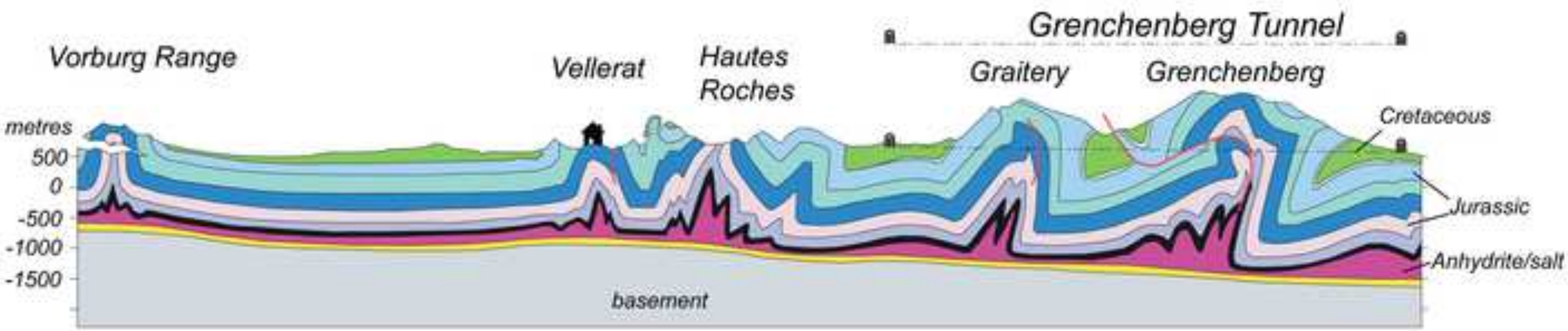


Figure 14

Click here to access/download;figure;Fig 14 literature.jpg

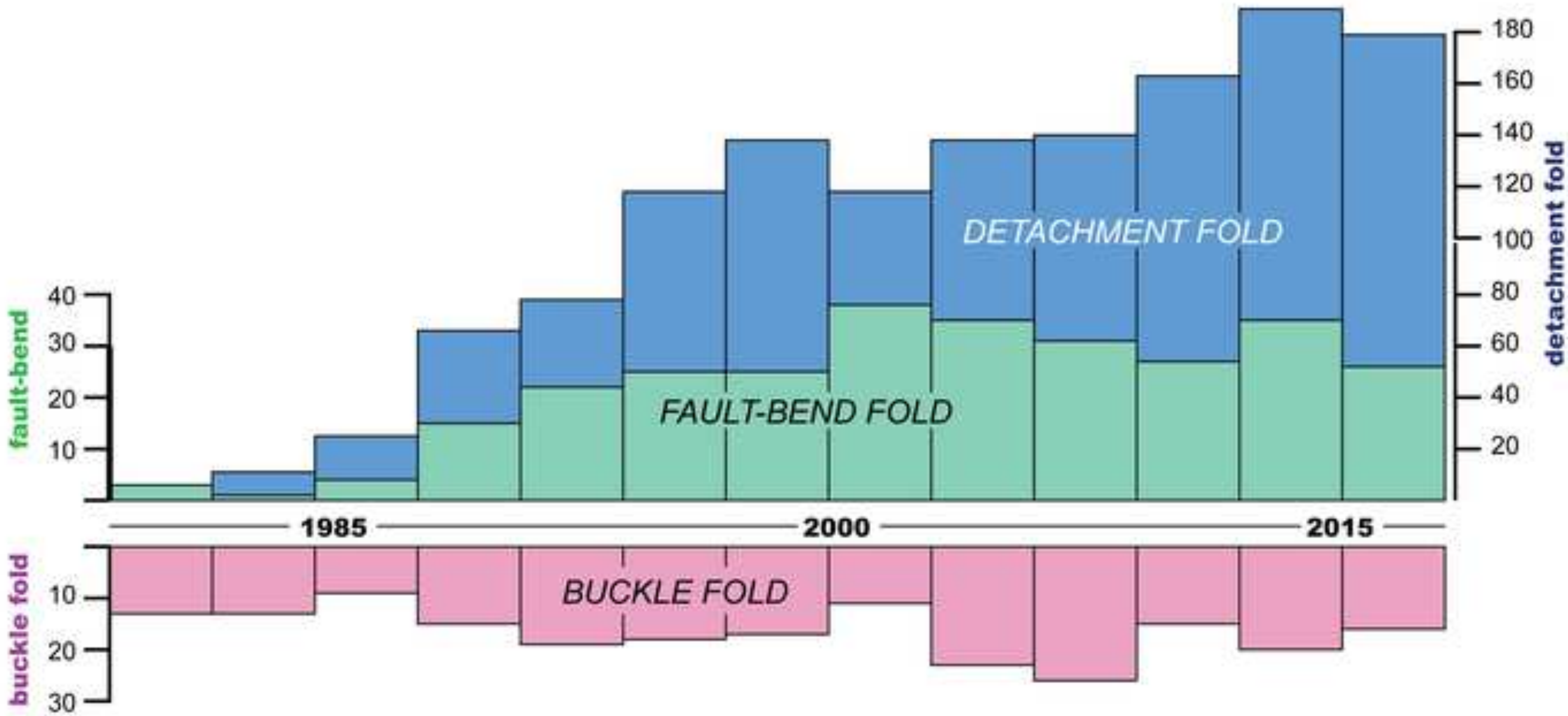
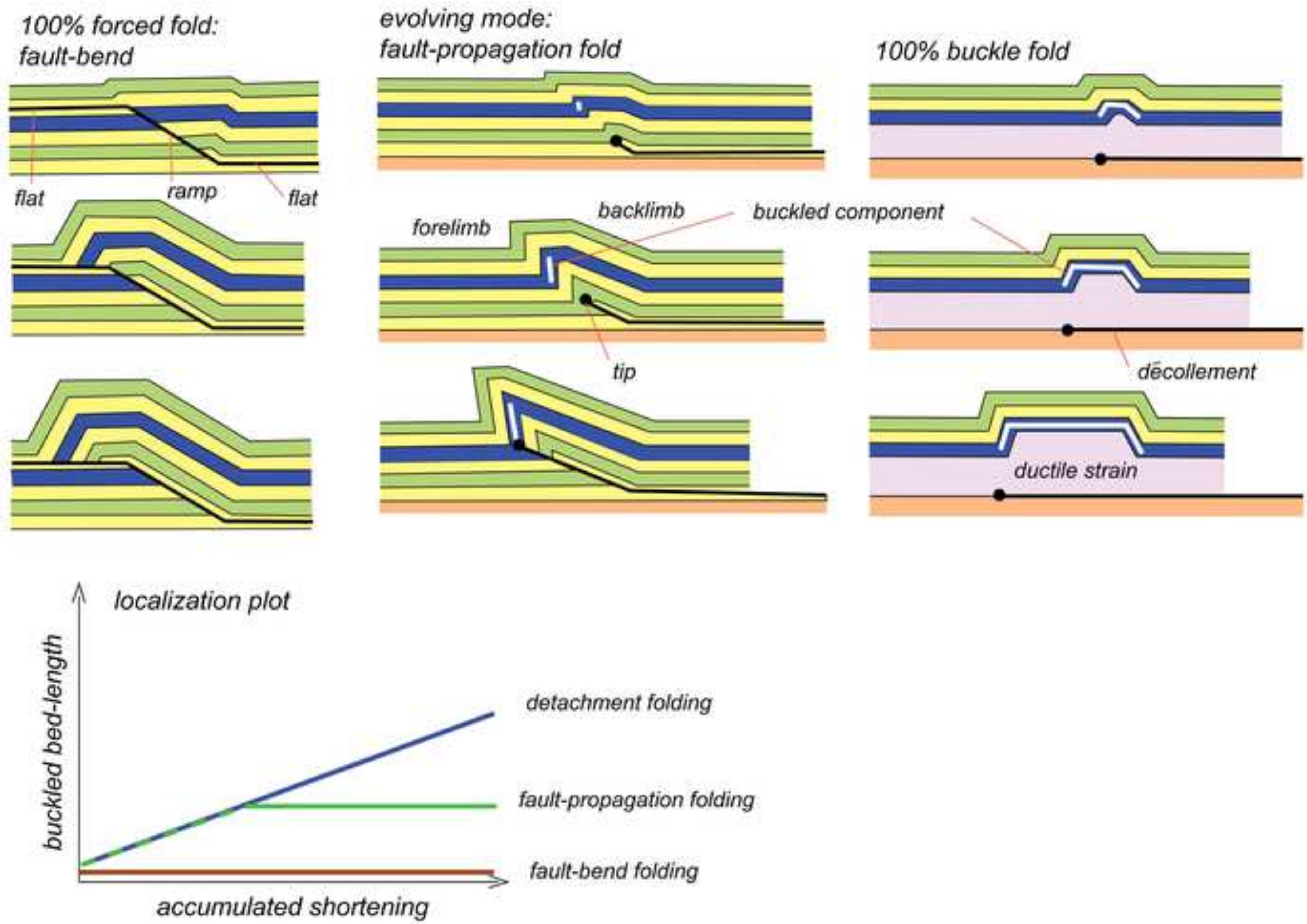


Figure 15


100% forced fold:
fault-bend
flat
ramp
flat
evolving mode:
fault-propagation fold
forelimb
backlimb
tip
100% buckle fold
buckled component
décollement
ductile strain
localization plot
buckled bed-length
accumulated shortening
detachment folding
fault-propagation folding
fault-bend folding